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STRUCTURE AND DIELECTRIC PROPERTIES OF SURFACE SNOW ALONG THE TRAVERSE ROUTE FROM COAST TO DOME FUJI STATION, QUEEN MAUD LAND, ANTARCTICA

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Abstract: Stratigraphical observations were carried out on the surface snow from the coast to the ice divide, Dome Fuji Station, in the summer of 1994/1995, to provide microwave remote sensing with ground truth data. Stratification, grain size and dielectric properties were measured in 1 m-deep snow pits excavated every 30–40 km of the 1000 km-long Dome Fuji Station traverse route. There exist three regional characteristics in the altitudinal distribution of the averaged real part of the dielectric constant ε' : a constant value in the coastal region, a higher value in the intermediate region, and a gradual decrease in the higher region. According to the measured snow properties indispensable to the utilization of microwave remote sensing, the dry snow zone of the studied area is divided into three parts: *a region of compacted snow and solid-type depth hoar* (1000 to 2000/2300 m a.s.l.), where spatial and vertical distribution of various snow properties are uniform; *a region of wind-packed snow and skeleton-type depth hoar* (2000/2300 to 3500 m), which is characterized by spatial alteration of the glazed surface and the stratified depth hoar layer; *a region of interbedded skeleton- and solid-types depth hoar* (higher than 3500 m) where the seasonal stratification of snow is characterized by thin-hard summer and thick-soft winter layers.

1. Introduction

The recent development of satellite-born remote sensing sensors has made it possible to survey polar ice sheets sufficiently both in time and space. Both active and passive microwave sensors can monitor the ground irrespective of weather conditions and are believed to detect not only superficial but internal features. In the Greenland ice sheet, for example, backscatter signatures of C-band SAR have made it possible to classify the superficial zonation of the ice sheet on the basis of internal melt-features (FAHNESTOCK *et al.*, 1993). In Antarctica, both the gradient and polarization ratios, determined by combinations of brightness temperatures of SMMR, are related to the grain size and stratification of surface snow, respectively (SURDYK and FILY, 1991, 1993).

The backscattering coefficient of SAR from the ice sheets is determined by both surface and volume scattering: the former depends on surface roughness and dielectric properties of snow, the latter on internal structure of snow including density, size and shape of grains, and the change of dielectric properties controlled by impurities and water content (MATSUOKA *et al.*, 1995). In addition to the theoretical and experimental approaches, it should be necessary to compare the satellite data with various ground properties for better understanding of microwave remote sensing.

This report provides the structure and dielectric properties of surface snow as a function of altitude along the traverse route from the coast to Dome Fuji Station, the highest point of Queen Maud Land, Antarctica. The first 250 km of the route (route S-H-Z) was opened in the late 1960's, and sufficient data on the surface snow have been collected repeatedly, while the route further inland has been less frequently traced since the first big traverse from the coast to the South Pole (FUJIWARA and ENDO, 1971).

2. Methods

Following the preliminary observation of surface snow between the coast and the Relay Point (MD364) in the summer of 1993/1994, detailed observations were conducted in 1 to 2 m-depth snow pits excavated approximately every 30–40 km along the traverse route from the coast (S16) to Dome Fuji Station (MD732) during the period from October 26, 1994 to February 8, 1995 (Fig. 1). There were 38 observation points. In the following discussion, data from the upper 1 m of the profile will be presented because most of the profiles were 1 m or somewhat deeper.

In each excavated profile, stratigraphy and snow type were described according to the stratigraphic nomenclature of WATANABE (1978a) which was established by the systematic observation of surface snow in Queen Maud Land. Grain size was measured in

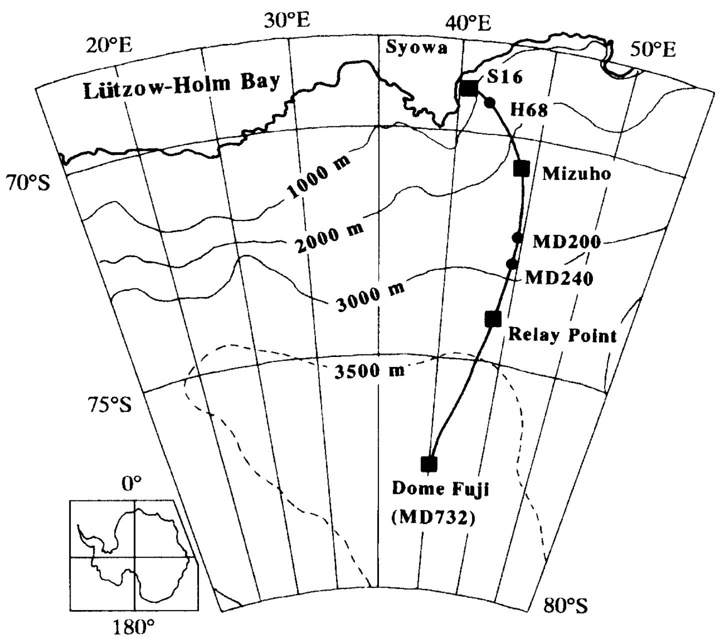

Fig. 1. Location map of the traverse route from the coast (S16) to Dome Fuji Station (MD732) and that of the representative snow profiles shown in Fig. 3.

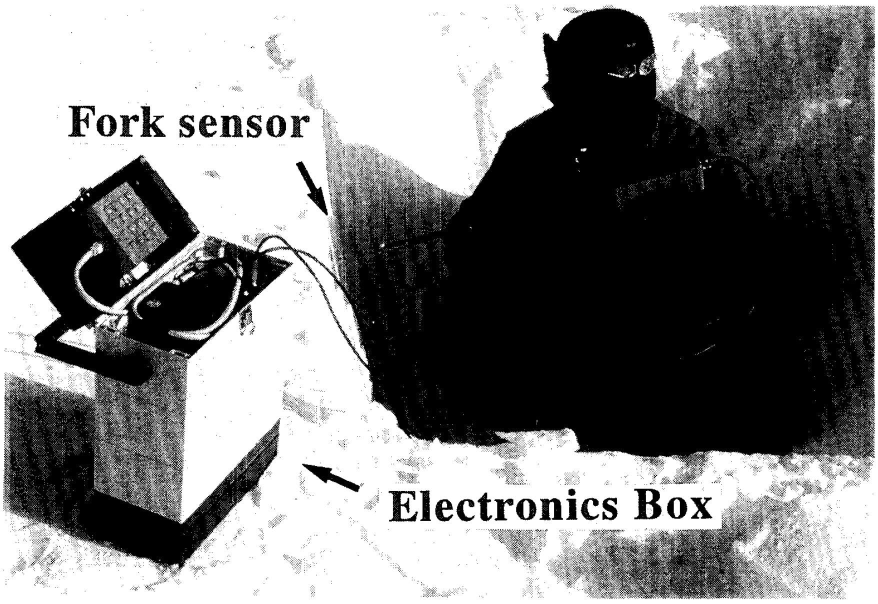

Fig. 2. Operation of the measurement of the dielectric properties of snow by using Snow Fork.

each unit layer to an accuracy of 0.5 mm with a grain-size gauge and a hand lens.

Dielectric properties of the snow were measured every 2 cm along the vertical walls of the snow pits using a "Snow Fork" (Fig. 2). To avoid the influence of holes made in the previous measurement, we slightly moved the point of measurement horizontally. The Snow Fork is a radiowave sensor for determining the density and wetness profile of a snow pack with a single measurement, based on the measurement of the dielectric properties (real and imaginary part) of snow around 1 GHz (SIHVOLA and TIURI, 1986). It consists of a resonator having a shape of 6 cm-long spikes with 18 mm space in between. The range and accuracy of the measurement are from 1.00 to 2.90 and 0.02 for the real part ε', and from 0.000 to 0.150 and 0.002 for the imaginary part ε''. It was specially designed to be able to operate under a cold environment as low as –40 °C which was the lowest air temperature in actual operation in the field. Fifty measurements were made in profile of 1 m depth.

Since the water content in the snow studied here was zero, namely the snow was dry, the imaginary part of the dielectric constant was always less than 0.010, and showed no variations. Therefore, we discuss only the real part ε' in this paper.

3. Results

3.1. Snow stratigraphies at four representative locations

Figure 3 shows four representative profiles of the surface snow in the study area. In this figure, the width of the columns represents the grain size of each unit layer. The term "unit layer" is defined by both upper and lower boundaries indicating a hiatus in the accumulation process (WATANABE, 1978a). Boundaries between unit layers denoted by solid and dotted lines are drawn whether there exist thin crust layers with a thickness

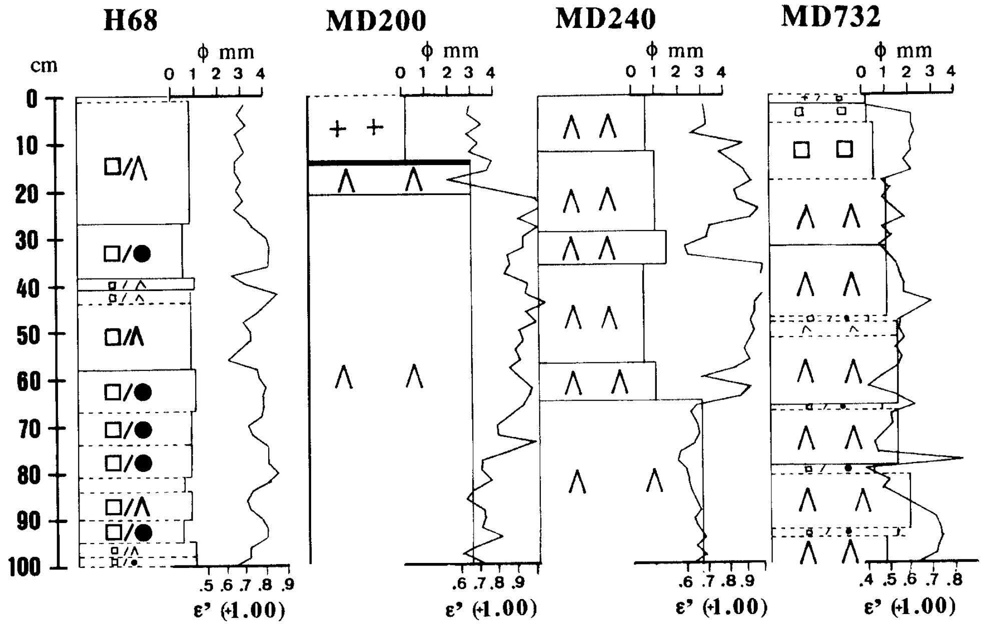

Fig. 3. Representative snow profiles obtained in this study. The columns and their widths indicate the stratification together with snow type and snow grain size, respectively. The right-hand profile shows the real part of the dielectric constant ε'.
Legend: ●: compacted snow, □: solid-type depth hoar, ∧: skeleton-type depth hoar, +: new snow. Two symbols divided by a slash (/) mean the combination of the two snow types.

of 0.5 to 1 mm or not. In case that the boundary was composed of multilayered ice crust as thick as 2 mm or more, it was defined as glazed surface and shown as a thick solid line. The profiles of the real part ε' of the dielectric constant are shown at the right hand side of the columns.

Site H68 (1160 m a.s.l.) is located slightly above the dry-snow line (700–1000 m a.s.l.; WATANABE, 1978b) and falls in the dry snow zone. The profile is characterized by a series of uniform unit layers partly bounded by thin crusts. The snow grains are dominated by the compacted snow and the solid-type depth hoar, and grain size is almost constant with an average value of 1 mm. In this site, the vertical variation of ε' is not large.

MD 200 (2788 m a.s.l.) exists in a highly eroded region due to the influence of katabatic wind. A 2 mm-thick glazed crust develops at the depth of 14 cm from the surface. The layer is underlain by uniform depth hoar 3 mm in size and skeleton-type in shape. The values of ε' of the snow increase sharply below the glazed crust, although considerable variations can be found. This type of snow stratigraphy was also found at Z40 (1997 m a.s.l.) and MD180 (2848 m a.s.l.), all of which are characterized by intensive development of the glazed surface underlain by a homogeneous depth hoar layer.

The stratigraphy at MD 240 (2890 m a.s.l.) is characterized by an alteration of thick-hardened and thin-softened depth hoar layers. The former is ascribed to "hard depth hoar" (AKITAYA, 1974) of smaller skeleton-type grains, while the latter has larger loosened ones. It is reported that the harder layer is formed in winter by wind, while the softer is formed in summer (WATANABE, 1978a). In the region affected by katabatic wind, spatial alteration of the MD200-type and MD240-type profiles is commonly found. Vertical variation of ε' is also large at this site.

At Dome Fuji Station (MD732; 3836 m a.s.l.), snow stratigraphy is considerably different from that at lower elevations. Here, a thick skeleton-type depth hoar layer is interbedded with a thin solid-type depth hoar layer. The former is characterized by loosened and enlarged grains, the latter is by hardened and smaller ones: the profiling is opposite to that observed at site MD240. A set of two layers may correspond to the annual layer, because the water-equivalent amount of one set coincides well with the estimated annual accumulation rate of 3.2 cm/a by AGETA *et al.* (1991). One set of layers can be explained to be seasonal by considering the following climatic and glaciological features at Dome Fuji Station: a relatively clear and calm summer induces sintering of surface snow and, hence, compacts the summer layer to be thinner, while strong radiative cooling and snowfall in winter make the winter layer thick and loose. A similar explanation was applied to the snow profile at the Plateau Station (3620 m), some 250 km to the south of Dome Fuji Station (KOERNER, 1971). The vertical variation of ε' is also large, and, especially, the thin solid-type depth hoar layers show the peaks of ε' values.

3.2. Altitudinal change of unit layers

A unit layer does not necessarily mean an annual or a seasonal layer. WATANABE *et al.* (1979), for example, reported that approximately 2 to 12 unit layers were formed in a year between 1000 and 2000 m altitude. The sequence of unit layers is, however, very important from the view point of remote sensing, because the boundary of unit layers reacts as an interface between different dielectric materials.

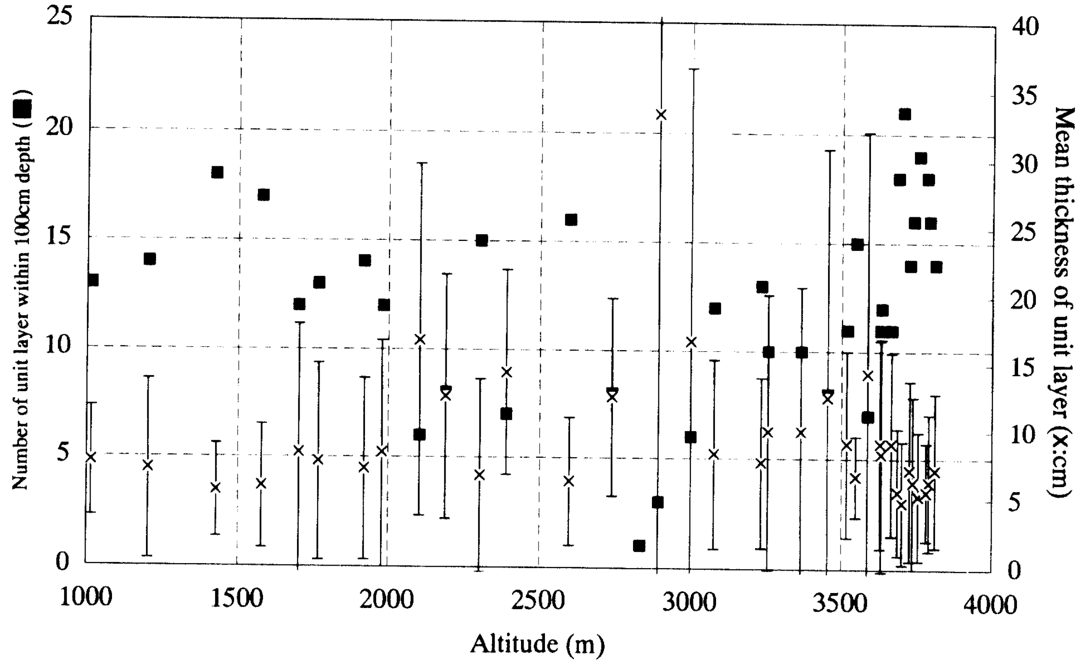

Fig. 4. Altitudinal distribution of the number (■) and the mean thickness (×) of unit layers within upper 100 cm depth. Bars around the mean thickness show the standard deviation.

Figure 4 shows the altitudinal change of the number of unit layers within 100 cm and the mean thickness of the layers together with standard deviation. The number of unit layers is 15 in the coastal region below 2000 m altitude. The number then varies between 2000 m and 3500 m, ranging from 1 to 16. Above 3500 m, it suddenly increases to 20.

The mean thickness of a unit layer has negative correlation with the number of layers. The deviation of the thickness within 100 cm depth is slightly larger in the region between 2000 and 3500 m.

3.3. Altitudinal change of grain size

The grain size in snow profiles changes considerably along the traverse route (Fig. 5). From the coast to the altitude of about 2000 m, the average grain size is almost constant: it varies from 0.7 to 1.2 mm with a standard deviation from ±0.2 to ±0.6 mm. The uniform distribution of grain size is explained mainly by the uniform snow crystal type which is dominated by slightly developed solid-type depth hoar.

The average grain size varies considerably in the katabatic wind region between 2000 and 3500 m in altitude where it changes from 0.6±0.5 mm to 2.7±0.9 mm. The larger grain size was observed at site where remarkable development of glazed surface was found. The smaller grain size was encountered at sites where the snow profiles are composed of relatively thinner unit layers of depth-hoar. At the sites, frequent existence of crust layers between the unit layers is considered to have interrupted the migration of vapor, which has made the development of depth hoar less active. The characteristics of this altitudinal region are spatial alteration of smaller and larger grains in the snow profiles as already mentioned in Section 3.1.

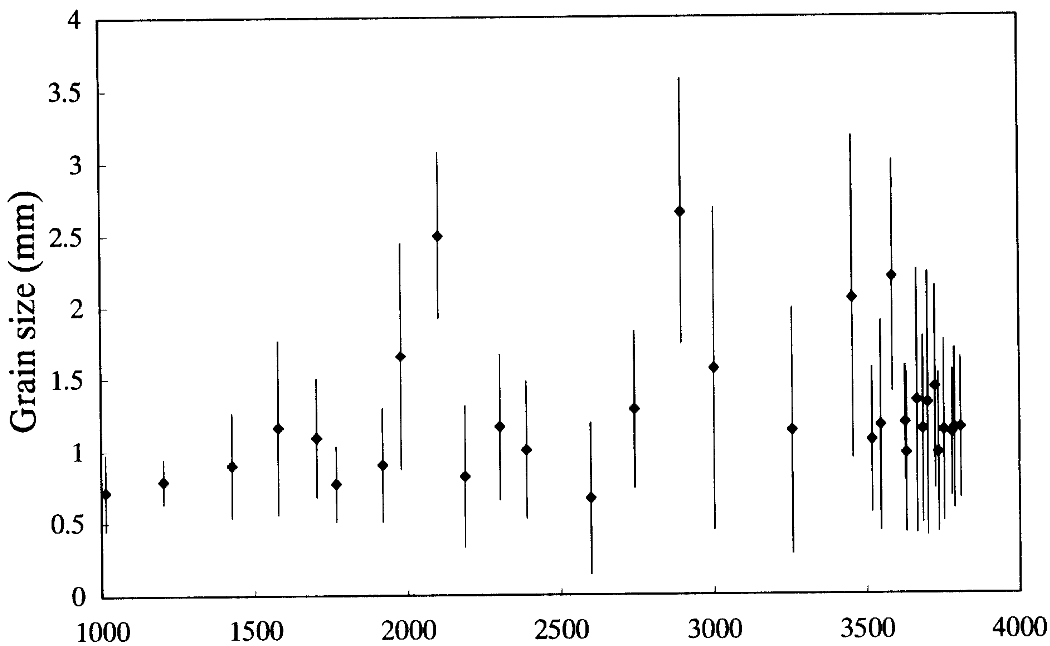

Fig. 5. Altitudinal change of the average grain size within upper 100 cm depth of snow. Bars are the standard deviation.

The grain size becomes very uniform above 3500 m altitude. It has an average value of about 1.3 mm, although the standard deviation is large (±0.8 mm). This is because the profiles are composed of sequences of fine-grained summer layers and coarse-grained winter layers as shown at location MD732, Dome Fuji Station (Fig. 3).

3.4. Altitudinal change of the real part of the dielectric constant

Figure 6 shows the altitudinal change of the averaged dielectric constant ε' of the surface snow. To investigate the altitudinal change of the values, each vertical profile of ε' at all locations was shown as an average value with standard deviation implying the degree of vertical variation.

Initially, the value of ε' is almost constant with the value of 1.70 between 1000 and 2300 m altitude. It then increases to 1.85 in the altitudinal range of 2300 to 3000 m. The value gradually decreases inland from 1.75 to 1.55 at Dome Fuji Station (MD732). The standard deviation seems to increase inland until the altitude around 3000 m. Above the altitude, it disperses from place to place.

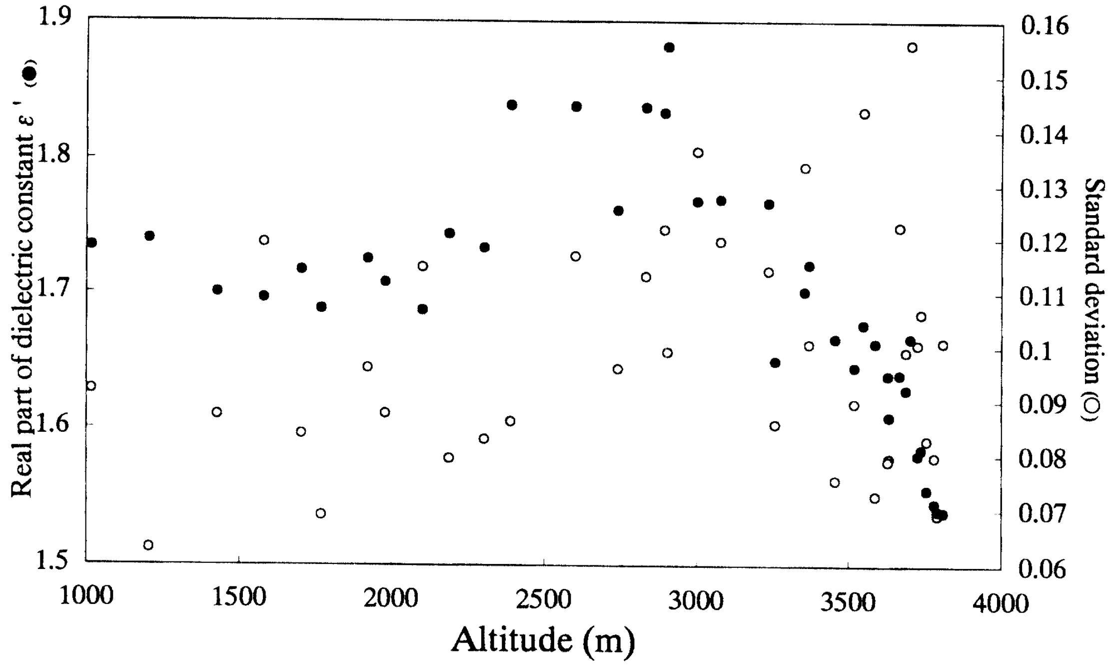

Fig. 6. Altitudinal change of the average values (●) and standard deviations (○) of the real part of dielectric constant of snow.

4. Discussion

4.1. Comparison of the dielectric constant ε' with snow densities

In Antarctica, dielectric properties of surface snow have scarcely been measured; this makes it difficult to check the reliability of the values shown in the previous section. The values are, therefore, compared with snow densities so far observed in Queen Maud Land, depending on the experimental fact that the dielectric constant of dry snow at high frequency is dependent mainly on the density of snow (Tiuri *et al.*, 1984).

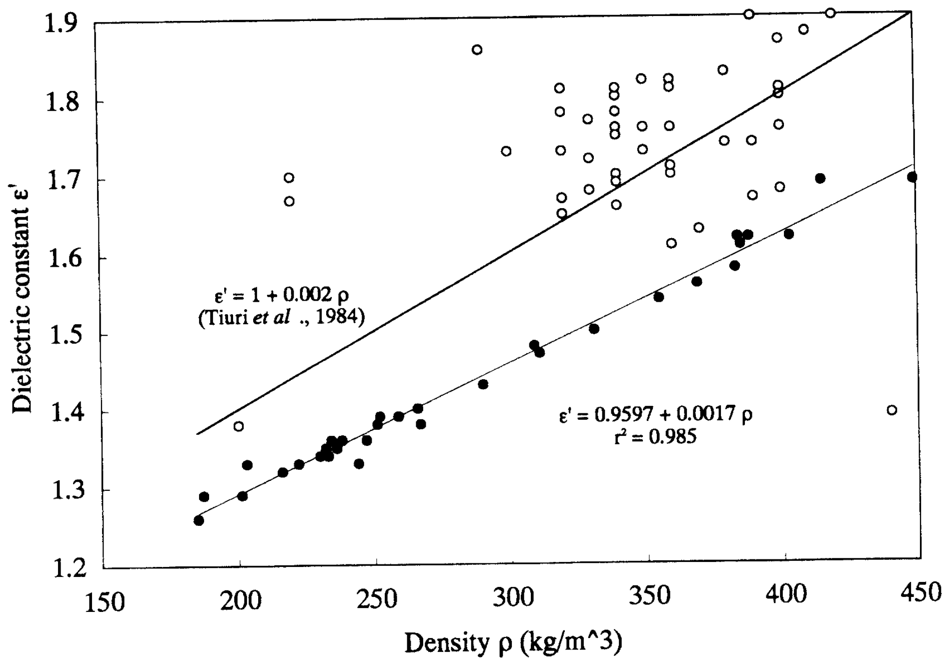

Fig. 7. Comparison between the real part of the dielectric constant ε' of dry snow measured by Snow Fork and the density ρ (kg/m³) measured by the weighing method for the Antarctic skeleton-type depth hoar (○) and the Japanese compacted snow (●).

Before the comparison, the values of the real part of dielectric constant ε' measured by Snow Fork were compared with snow densities ρ (kg/m³) measured by a traditional weighing method (Fig. 7). Open circles denote the values obtained from the skeleton-type depth hoar sampled at MD 364, MD 320, MD 240, MD 180, MD 120 and MD 40. To check an influence of a shape of snow grain, values from dry compacted snow, sampled at Sekiyama of Nagano Prefecture of Japan in the winter of 1996 using the same Snow Fork, were also shown as solid circles. It is clear that the dielectric constant ε' has a good correlation ($r^2 = 0.985$) with the density for the compacted snow as expressed by;

$$\varepsilon' = 0.9597 + 0.0017\ \rho. \qquad (1)$$

In contrast, although it showed bad correlation, the values of the skeleton-type depth hoar seem to fit a practical equation expressing the relationship between the real part of the dielectric constant ε' of dry snow at microwave frequencies and the density (TIURI *et al.*, 1984) as;

$$\varepsilon' = 1 + 0.002\ \rho. \qquad (2)$$

This probably indicates that the dielectric constant ε' measured by Snow Fork can be affected by the shape of crystals. According to a theoretical study on the relationship at 1 GHz frequency (SIHVOLA *et al.*, 1985), a disk-shaped snow structure gives higher ε' value than a spherical one if the snow densities are the same. Our result seems to be consistent with the theory since the compacted snow is much more spherical than the depth hoar.

It becomes possible now to compare our results with the bulk density of the surface snow obtained in different years by different researchers along the traverse route in Queen Maud Land by converting the dielectric constant into the density using the eqs. (1) or (2). Since the snow grains dominated below the altitude of approximately 2300 m are both the compacted snow and the solid-type depth hoar, eq. (1) was used for the conversion. Above the altitude of 2300 m, the snow is mostly the skeleton-type depth hoar, therefore, eq. (2) was used for calculation.

Figure 8 shows the density calculated and two averaged values of the bulk density measured along the traverse route. It should be noted that the comparative data are sampled at the same route between the coast and Mizuho Station and at different traverse routes beyond the Station, namely higher than 2232 m, although the data are plotted against the same altitudinal axis.

Snow density in the coastal region (up to 2300 m in altitude) shows fairly constant value of approximately 450 kg/m^3, while in the katabatic wind region from 2300 to 3000 m, it becomes slightly lower with a value of 420 kg/m^3. The most interesting feature is the gradual decrease of density above the altitude of 3000 m, where the value decreases from 400 to 280 kg/m^3 toward Dome Fuji Station (MD732).

Our results generally coincide with previous ones, except for the inland region above the altitude 3000 m where YAMADA and WATANABE (1978) gives the average value of 350 kg/m^3 based on the observation made by ENDO and FUJIWARA (1973). The gradual decrease of our result is probably explained by the decrease of air temperature toward the south. Since the wind in this inland region is very weak, densification of the surface snowpack is ascribed to a sintering of snow, which is very sensitive to temperature. Thus the colder the site, the slower the densification.

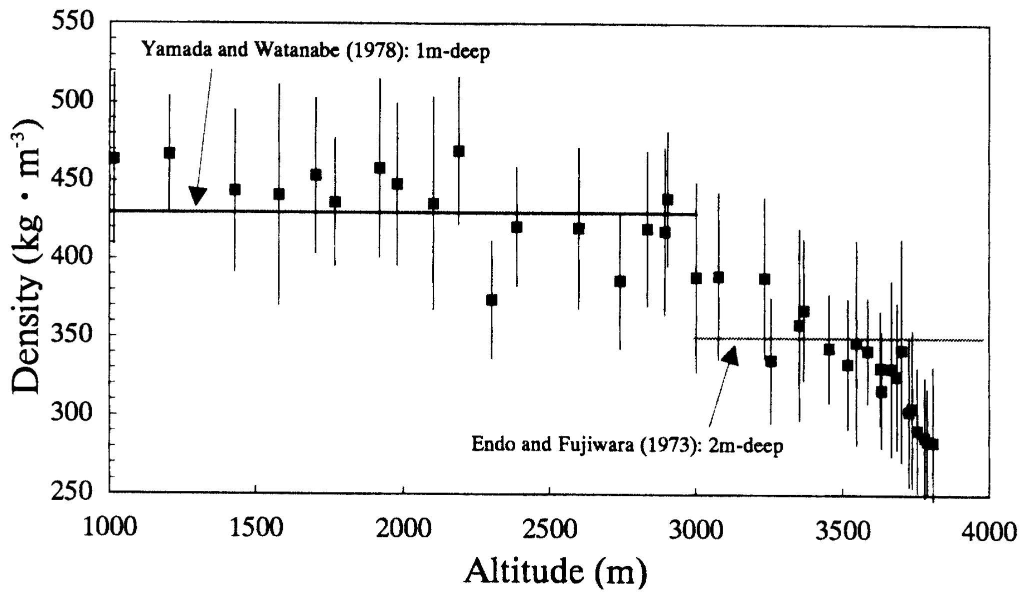

Fig. 8. Altitudinal change of the calculated snow density. Densities obtained by previous studies are also shown for comparison. It should be noted that values by ENDO and FUJIWARA (1973) are those obtained from the surface to the depth of 2 m.

4.2. *Zonation of the ice sheet surface*

Based on several properties of surface snow, possible forms of zonation of the ice sheet have been proposed by several authors (Table 1). Most of the studies have divided the dry snow zone into three regions: a region less influenced by katabatic wind, a region susceptible to intensive katabatic wind, and a region beyond the influence of katabatic wind.

The present results, dependent on the stratigraphy, the number of unit layers, the grain size, and the dielectric constant within the upper 100 cm of surface snow, lead to a similar zonation to previous studies, although the altitudes of the regional boundaries are different from those in the previous studies. There are three regions named mainly according to snow type because the snow type is of primary importance both for genetic classification and for remote-sensing of the ice sheet surface.

The region from the coast (1000 m) to altitude 2000 to 2300 m is defined as a *"region of compacted snow and solid-type depth hoar"* where altitudinal changes of the stratification, the number of unit layers, the grain size, and the variability of the dielectric constant of snow are small.

From 2000–2300 to 3500 m altitude, the area is classified as a *"region of wind-packed snow and skeleton-type depth hoar"*. Characteristics of the region include alteration of the area of glazed surface underlain by developed depth-hoar and the stratified depth hoar. Most of the properties vary spatially in this region due to the aerial distribution of the two snow types.

Above 3500 m, the influence of katabatic wind becomes small (AGETA *et al.*, 1989); thus, the surface of the ice sheet becomes as flat as that in the coastal region. However, the snow type is completely different from that in the lower area; therefore, this area is named as a *"region of interbedded skeleton- and solid-types depth hoar"*. Distinctive seasonal layers are identified as thin-hard summer and thick-soft winter layers. The situation is completely different from the stratification of the lower region where the summer and winter layers become soft and hard, respectively (WATANABE, 1978a).

The principal factors which delineate the three regions are considered to be the amount of snowfall and the influence of the katabatic wind. If it becomes possible for microwave remote sensing to detect the three regions by using the snow properties men-

Table 1. Proposed glaciological zonations of Queen Maud Land, East Antarctica.

Criteria of zoning	Altitude (m): 0, 500, 1000, 1500, 2000, 2500, 3000, 3500, 4000	References
Surface features		Watanabe, 1978b
Stratigraphy	*Lowest region*; *Intermediate region*; *Highest region*	Watanabe, 1978a
Mass balance	*Continuous acc. zone*; *Sporadic acc. zone*; *Calm acc. zone*	Yamada & Wakahama, 1981
Glaciological features	*Coastal region*; *Stationary katabatic wind region*; *Inland region*	Shimizu *et al.*, 1978
Depositional environment		Furukawa *et al.*, 1994
Surface snow properties	*Compacted snow & solid-type depth hoar*; *Wind-packed snow and skelton-type depth hoar*; *Depth hoar*	This study

tioned here, it should be possible to monitor the change of the amount of snowfall and the influence of the katabatic wind. For this purpose, the next step will be to compare the microwave data with the detailed ground sensed data mentioned here.

5. Conclusions

For the interpretation of microwave remote sensing in the Antarctic ice sheet, measurements of the stratigraphy, grain size and the dielectric properties of the surface snow were conducted from the coast to the highest point, Dome Fuji Station, during a relatively short time in the summer of 1994 / 1995. The dielectric properties were measured by the hand-held radiowave sensor "Snow Fork".

Four types of snow stratigraphies were identified. They are characterized by the sequences of unit layers, the types and the size of snow grains, and the degree of densification. Considerable variation in the real part of the dielectric constant ε' of the snow was found in the vertical profiles of the snow pits except for the coastal region, although the imaginary part ε'' showed little variation. There exist three regional characteristics in the altitudinal distribution of the averaged values of ε'; the constant value in the coastal region, higher value in the intermediate region, and the gradual decrease in the higher region.

Depending on the snow properties mentioned above, the following zonation of the ice sheet is proposed.

1) Above the dry snow line at altitude 1000 m, a *"region of compacted snow and solid-type depth hoar"* extends up to 2000–2300 m where various snow properties are almost uniform.

2) The altitude zone from 2000 or 2300 to 3500 m is defined as a *"region of wind-packed snow and skeleton-type depth hoar"*. It is characterized by the spatial alteration of glazed surface underlain by developed depth hoar and the stratified depth hoar layers. This area is under the influence of katabatic wind.

3) Above 3500 m is a *"region of interbedded skeleton- and solid-types depth hoar"*, where seasonal stratification of snow is characterized by thin-hard summer and thick-soft winter layers.

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